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WATER-EPM: THE INCORPORATION OF WATER INTO AN ENERGY POLICY MODEL

Mary D. Schrot

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DISCLAIMER

WATER-EPM

THE INCORPORATION OF WATER INTO AN ENERGY POLICY MODEL*

Significant amounts of water are consumed as energy is transported from resource regions and processed into gasoline, electric power, etc., available for end-use in a demand region. Indeed, particularly in certain regions, water, even more than energy resource materials such as coal, gas, or uranium, may eventually constitute a prime constraint on the energy available for end-use. Models designed to forecast energy supply and demand generally do not consider water resources explicitly. This paper addresses the feasibility and usefulness of integrating water into a particular model.

The Lawrence Livermore Laboratory (LLL) Energy Policy Model (EPM) is a regionalized, dynamic equilibrium model that represents the production, processing and transport of energy from resource extraction to end-use. This paper consists of a simplified look at the workings of the modeling system underlying the EPM, an overview of the EPM itself, a description of the manner of incorporating water into this model to form WATER-EPM, and a brief discussion of the issues which can be investigated using this augmented model.

THE MODELING SYSTEM -- A SIMPLIFIED DESCRIPTION

The software package underlying EPM is capable of handling extremely complex calculations which do not easily lend themselves to brief explanations. We will make significant simplifications in what follows.

Although EPM is a dynamic model, we will begin by considering a static representation of a trivially simple economy. Let us suppose that the only energy source in a small village is wood, and that there is a single producer, that is, one person who owns the resource, chops the wood, and sells it to the villagers. Since EPM is based on free-market economics, the apparent monopoly-monopsony aspects of the example economy will be ignored.

Using the conventions of EPM, we would conceptualize this situation as in Figure 1 and would describe it in a network file as follows:

```
DEFINE    MODEL WOODPROD
          MARKET ENDUSE(WOOD)
          PROCESS WOODCHOP (;WOOD)
          END
```

These instructions name the submodel, assign the material (WOOD) to a class (ENDUSE) of market nodes, and identify WOODCHOP as a resource production process with no input (before semicolon) and with the output WOOD.

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EPM is largely driven by resource depletion. We picture the resource producer taking into consideration various costs, the necessity of reseeding if he chops down large numbers of trees, and other marginal cost considerations which would determine the price to charge for various amounts of wood -- perhaps $50.00 a cord, if he produced a hundred cords, $60.00 a cord for 120 cords, because of his additional costs for reseeding, etc. He would thus come up with a supply curve like that in Figure 2, describing increasing marginal costs as production grows.

In the simplest case, the villagers would decide how much they want, pay the woodcutter the price from his curve, and the matter would be settled. In a slightly more elaborate case, the village council would survey the villagers, determining how many cords would be purchased if the price were $100 per cord, how many additional ones if the price were $90.00, $80.00, etc. In this way a demand curve would be formed resulting in the curves shown in Figure 3.

Let us suppose now that the resource owner has a supply curve and the villagers have a demand curve but neither knows the other's curve. A negotiation is to take place between a village elder and the resource producer. They will bargin until a price and a quantity have been agreed upon. The elder suggests the quantity Q_1, and, to determine his response, the resource owner takes that quantity along the bottom line of his graph, moves up to his supply curve, and sees that P_1 is the price that would go with it. He then tells the elder that the wood would be available at price P_1. Next the elder goes to his demand curve and sees that price P_1 corresponds to quantity Q_2 which is the quantity he then proposes to purchase at price P_1. This process is continued until an equilibrium is reached. Figure 4 shows some steps of the procedure. This simple iterative process indicates the method of solution that the modeling system uses.

We can now introduce the manner in which the system models government policy regarding taxes and both price and quantity controls. If a tax were imposed on the cost of the wood, the effect, from the buyers' viewpoint, would be to raise the supply curve, that is, the cost at which wood was supplied to the end-user. This would shift the equilibrium as shown in Figure 5. Without the tax, the equilibrium was at quantity Q_0 and price P_0. With the tax, the quantity drops to Q_1, and the resource owner's marginal cost drops to P_1 per unit, while the price paid by the consumer is now P_2 per unit, the difference $P_2 - P_1$ representing the tax.

Suppose a regulatory agency wished to limit the amount of wood to Q_1 for environmental or other reasons. It would be possible to accomplish this by a tax as shown. Alternatively, the agency could simply forbid the selling of more than the specified amount Q_1. The wood resource owner would have been willing to sell this amount at P_1 per unit. Buyers, however, are now willing to pay price P_2. The resource owner could simply charge P_2, thus reducing the demand. On the other hand, if the price is being controlled at the P_1 level, the demand will actually be for Q_3 units.

In this case the model will introduce a shadow (or decision-making) price P_2 so that purchasers will decide how much to buy as if the price were P_2, but will actually pay P_1.

Let us now refine our simple model slightly, assuming the wood is bought by two classes of users (Figure 6). Some of it is used for cooking (i.e., necessity) and some is used in fireplaces for aesthetic and recreational purposes rather than actual heat and necessity. The resource owner still has a supply curve similiar to that before. Each of the user groups has a distinct demand curve as shown in Figure 7. Those who buy wood for necessity, such as cooking, will reduce their usage only slightly as the price gets higher. Those for whom the uses are optional will change their usage level quite drastically if the wood becomes expensive. The two curves are aggregated into a single demand curve, which is the one which will interact with the resource owner's supply curve.

Now let us consider the tax effects in this situation. The effect of a tax looks the same as before when we are considering the aggregate demand curve. However, if we separate out the effects into the two separate demand curves, we see that the cooking users have dropped back their usage level very little whereas the fireplace users have dropped their levels quite considerably (Figure 8). If the regulatory agency wished to cut down the level of wood usage, a tax would accomplish this with only minor economical disruptions, while price and quantity controls could cause less predicable, potentially more disruptive reallocations.

Another realization of this model would be a division of gasoline users into those who use cars for absolute necessities, that is, commuters with no alternative transport available, traveling salesmen, etc., and a second category of users such as housewives taking their children to places that could be reached by bus or by bicycle, etc. If a tax is put on the gasoline, the essential users will maintain their level of usage while the discretionary users will reduce consumption. If, however, the control of the quantity is done not by taxes but by a mechanism such as gas lines, the usage will redistribute in a completely different fashion and may be much more disruptive.

Now let us consider another case which looks equally simple but actually has additional complexity. As shown in Figure 9, it would be possible to have two suppliers of wood to the same village. Each supplier would have his own supply curve based on his own costs, rate of return, etc. If supplier one is to sell Q_1 cords of wood he will charge P_1 dollars per cord, where $P_1 = .2Q_1 + 30$. Supplier two, when supplying Q_2 cords, will charge P_2 dollars per cord, where $P_2 = .1\ Q_2 + 45$.

The aggregate price which will be seen by the end users is

$$P = \frac{P_1Q_1 + P_2Q_2}{Q_1 + Q_2}$$

For the moment let us assume the end-users do not have an elastic demand curve but simply wish to purchase 200 cords of wood. A user-specified positive number , called the market share parameter, which reflects uncertainty in price perceptions, determines the shares allocated to competitors. (In actual EPM calculations, other parameters describe time lags in responding to price changes.)

In the case at hand,

$$Q_i = \frac{P_i^{-\gamma}}{P_1^{-\gamma} + P_2^{-\gamma}} \cdot 200$$

where i = 1 or 2.

In modeling this situation, the user would specify a starting quantity for each of the producers. In our example, since the producers would not actually know that the total demand was 200, each one of them might start with 110. The iterations leading to equilibrium would then be of the form shown in Table 1.

TABLE 1

Q_1	P_2	Q_2	P_2
110	52.00	110	56.00
104	50.80	96	54.60
107	51.40	93	54.30
105.5	51.10	94.5	54.45
106.3	51.26	93.7	54.37
.	.	.	.
.	.	.	.
106.035	51.20	93.965	54.40

The cases discussed above provide a static illustration of the main mechanisms that occur in the model. Let us now take a brief look at the dynamic situation. Suppose we go back to the simple economy where a single wood producer supplies end users directly. We will suppose we are modeling a three year horizon with one year time periods. The resource producer has a cumulative supply curve, showing marginal costs as a function of cumulative production. If, at a given time, precisely 200 cords of wood have already been produced, his marginal cost (Figure 10) is $45.00 per cord; at the point in time when he has produced precisely 300, his marginal cost is $50.00, etc. The model assumes marginal cost pricing.

Let us suppose the starting estimates for quantities are 110 cords in the first year, 120 in the second and 130 in the third. (Such estimates are input by the model user to initialize the convergence procedure.) We now look at the last time period. Since 230 cords of wood have already been produced by the time the third time period begins, the price (marginal cost) ranges from $46.50 to $60.00 as shown in Figure 11. Thus, if the assumption is that 130 units will be sold in this time period, the price will be $56.00 per cord. This price is sent up the network. We then go to time period two and do a similiar calculation obtaining $46.50 as the price. Again, in the first time period we obtain a price of $41.40. Each of these prices is sent up the network to interact with the end users' demand curves. The quantity calculations for each time period are done as in the previously discussed static case. However, a change in quantity in a early time period will change the appearance of the supply curves at all later time periods for the next iteration.

The economics of producing, transporting, and processing energy are described in terms of capital costs, rate of return, operating and maintenance costs, book life, debt life, and many other considerations. However, the general thrust of the type of calculations and of the nature of the iterative procedures in the model has been essentially covered in the above description.

THE ENERGY POLICY MODEL (EPM)

The prime use of the system described above has been LLL's Energy Policy Model (EPM). As an equilibrium model, EPM is driven by depletion of resources and by assumptions regarding demand growth, price and substitution elasticities, and future costs of technologies. The model is regionalized as indicated in Figure 12. Actually, several different regionalizations for resources, refineries, and end-uses have been superimposed. Thus, coal fields, oil and gas resources and others have been located in several areas throughout the country and refineries at six different points. Demands are disaggregated into the census regions of the U.S.

Corresponding to each main category of resource, such as coal or oil, to refineries, and to each main category of end-use, such as transportation, industrial, residential-commercial, and feedstock, there is a section in the network file describing the interrelation of the nodes. A parameter file gives the data base, that is, the economic parameters describing the costs of mining coal, refining oil, and so forth, as well as certain numbers that reflect assumptions on demand elasticities, and so forth. The program called INPUT takes the network and parameter files and from them builds a work file that includes a copy of each network section for each region that has been assigned to it. Transportation links are inserted as defined in the network and parameter files between regions. The total network has over 3000 nodes. Sections of the network look similar to that shown in Figure 13.

Once INPUT has created the network and assigned a sequencing order, that is, numbered all the nodes, the network is ready to be processed by the program SOLVE. At the bottom of the network, each resource node has been assigned a trial quantity for each time period. Using these initializing values, prices are calculated at resource nodes and sent on up the network. At each demand node at the top of the network a quantity is determined to go with the price that has been passed up the network. These quantities are then passed down through the network and at each market node that is fed by more than one process or technology a market share mechanism assigns shares to each of the technologies for each time period.

All of these calculations are being done essentially simultaneously for all the time periods. When prices are calculated, for example, at a resource node, they are started from the last time period and worked back so that the amount of the material, or resource, that has been depleted over time to that period is taken into consideration. It is also assumed that a resource owner is looking at future profitability of development, comparing its present value with current profitability, and adjusting his price upward if he could make more money by postponing development to the future than he could by selling now at a price based on his costs. The process is iterative, that is, what has just been described is one iteration toward the solution for a given case. The iterative process consists of going up the network calculating prices and coming down again calculating quantities. Relaxation mechanisms have been put into certain nodes to promote convergence.

The SOLVE program is allowed to run until very little change takes place on subsequent iterations. When convergence has been attained, the resultant work file can be processed by the other two programs in the software package --PRINT and PLOT. The PRINT program produces a file that shows a price and a quantity for each node in the network, for each of the ten time periods in the standard version of the model. These results are formated in a manner that facilitates tracing through the network. For the PLOT routine, one needs not only a work file but an instruction file specifying what nodes are to be plotted. For each node, or aggregation of nodes, that are to be plotted, the program produces one plot of dollar prices per million BTU against years and another plot of quantities used per year against years. The instruction file can specifiy aggregation of a great many types. It is possible, for example, to look explicitly at the market shares at a given node and determine the penetration of a new technology.

EPM, as its name indicates, is a policy analysis tool. Once a base scenario giving some plausible view of the future has been established, the main interest lies in the differential results between two runs in which a policy alternative has been tested. For example, one could consider ouptut with and without government price controls on certain fuels or with and without the availability of synfuels technologies on a given date at a given cost. Shortly after the Three-Mile Island incident, a comparison was made of the energy futures of the United States under prior assumptions about the development of nuclear power and under an assumption of a strong moratorium on such development. Comparative runs have also been made under assumptions that environmental considerations would force a stringent limitation on production of coal and/or use of coal for synfuel production. Methods for full quantification of the differenial costs and benefits between such runs have not yet been developed.

INCORPORATION OF WATER INTO EPM

The interactions of water and energy resources are a matter of increasing interest and concern. In addition to the current usage of water for power plant cooling, coal mining, and many other energy related activities, the plans that are being made for large scale production of synthetic crude oil from coal and from shale oil require enormous amounts of water. LLL and Stanford University, with support from the Electric Power Research Institute, are involved in what appears to be the first attempt to incorporate water into a large, regionalized energy model describing virtually the entire energy sector of the U.S. economy. This augmentation of EPM includes superimposing still another regionalization, that is, a description of water basins.

In the preliminary feasibility study, water information was added to the standard EPM only in what we called the Rocky Mountain region. We modified the EPM network by adding a water production process node leading to a water market (or material) node, which feeds into a dozen process nodes, each of which produces a new conceptual input material for an existing process node such as coal-fired power generation. Instead of the feedstock to this process being coal, as in EPM (Figure 14), it is a mixture, in specified proportions, of coal and water (Figure 15). The network specified a water component in all Rocky Mountain region inputs to power plants, processing and coal slurry pipelines. The resource curve for the production node, actually derived by aggregating data for two hydrologically distinct water resources, and the water-use coefficients determining the composition of each conceptual feedstock were provided by Nathan Buras (1), in conjunction with whom the scenario was designed.

Modifications at the software level were also necessary. Virtually all resources already represented in the EPM are subject to depletion and thus tend to become more expensive over time. All resource KINDs (node-associated sub-routines) in the standard EMS software reflect this so that, in the absence of learning, constant dollar prices are non-decreasing over time independent of any changes in annual consumption rate. The fact that water, expecially in the Rocky Mountain region, renews annually as the snow melts, necessitated the introduction of a new KIND designed especially for such an annually renewed resource. The new KIND, designated as RESANN for RESource ANNual, allows for a specified amount of material at a low marginal cost each year before more expensive extraction or production costs become active.

The test scenario provided that the price for a given year be calculated from the marginal cost of producing the last unit of water used that year which can be construed as assuming that all energy consumption of water would be junior to all other rights to the region's water. In suppressing price elasticity for the non-energy water consumption, the test scenario used in the study obviated the possibility of introducing new technologies in, for example, agricultural irrigation. The combination of assuming inelastic non-energy water use and marginal-cost pricing of water ignores any selling of water rights by agricultural interests. In other words, water allocated to non-energy use under this scenario can in no way be released to energy users.

Water consumption for energy transport and conversion in the Rocky Mountain region was modeled explicitly for coal slurry pipelines, coal- and oil-fired power plants, light water reactors, high-Btu coal gasification, coal liquefaction and shale oil upgrading. Water requirements for these processes are given in Table 2. The scenario is described not by way of justifying it but to provide a frame of reference for interpreting the output. The purpose of the study was the evaluation of EPM's ability to handle a hydrological scenario rather than the forecasting of energy production.

TABLE 2

WATER USE COEFFICIENTS
(acre-feet/quad)

Coal slurry pipeline	34,000
Fossil fuel power plants	395,000
Nuclear power plants	592,800
Oil shale conversion	61,700
Coal gasification, HBtu	103,000
Coal liquefaction	57,000

Run under the assumptions described above, the model allocated the water available for energy-related use among various existing and proposed technologies as shown in Table 3. The test scenario induces reduced power generation in the region by the end of the first decade of the 21st century and cuts back significantly on synthetic fuels production. This model run overcame a power deficit largely by importation of coal-generated power from the Great Plains, although increased electricity prices caused some decline in demand. As seen in Figure 16, shale oil production would level out at about 3.5 million barrels a day. A control scenario assuming essentially infinite quantities of cheap water showed shale production increasing to nearly twice that level.

The integration of water into EPM to form a preliminary WATER-EPM and the running of the test scenario demonstrate an initial capability for viewing economic interactions of water and energy. The basic model system, which was designed to facilitate both the introduction of new process types and easy iterations in the network, functioned well.

TABLE 3

ROCKY MOUNTAIN REGION WATER USE
(IN THOUSANDS OF ACRE FEET)

WATER FOR	1975	1980	1985	1990	1995	2000	2005	2010	2015	2020
SLURRY PIPELINES	0	0	0	9.56	17.0	22.8	27.7	24.9	13.8	8.46
GAS FIRED POWER	37.4	43.1	52.1	77.7	107.0	135.0	168.0	195.0	150.0	97.8
DISTILLATE FUEL POWER	87.7	49.0	27.4	21.8	15.9	11.1	7.61	5.13	3.24	1.96
RESIDUAL FUEL POWER	18.6	17.8	14.0	9.99	6.87	4.66	3.13	2.05	1.28	.79
COAL FIRED POWER	78.4	221.0	334.0	423.0	510.0	608.0	735.0	782.0	490.0	303.0
LWR	0	3.50	29.0	76.4	123.0	150.0	140.0	101.0	62.2	38.6
COAL GASIFICATION	0	0	0	0	.23	2.59	10.5	28.0	16.4	8.82
SHALE	0	0	0	3.35	27.7	77.2	190.0	397.0	395.0	380.0
COAL SYNCRUDE	0	0	0	0	.002	.022	.159	.785	1.63	2.55
NON ENERGY	13,200	14,900	16,700	17,700	18,700	19,700	20,700	21,200	21,800	22,100
TOTAL	13,400	15,300	17,200	18,300	19,500	20,700	22,000	22,800	22,900	22,900

The current use of LLL's economic modeling system to project energy constraints based on water by means of WATER-EPM involves further development of certain additional sub-rountines and full regional augmentation of the network accomplished in tandem with general planning of scenarios and testing for sensitivity.

Several extensions and additions to the EPM network are indicated. In addition to constraining water use through high prices, we will be able to present policy limitations, some of which can best be modeled by placing a quantity control on the water. The KIND called QCTRL activates a shadow or decision-making price when demand would otherwise exceed the limit. In each region, not only a QCTRL but additional nodes assigning water to its various uses are necessary to facilitate the availability of water data in output files produced by both PRINT and PLOT. Figure 17 shows the general form to be provided in each region.

Each region of the WATER-EPM must have the structure just described, with water feeding into all the energy processes for which this was done in the test scenario described earlier. Additionally, one may wish to include other energy processes which do indeed use water or to disaggregate hydrological regions within existing resource regions. This appears particularly apt within the Rocky Mountain region where the water from the Upper Colorado should be distinguished from that of the Upper Missouri Basin especially in terms of availability to shale oil processing.

The explicit modeling of transport of water, with associated costs, is being added. In some regions it will be pertinent to model water prices based upon averaged or rolled-in costs in accordance with regulatory decisions or other economic realities. A new KIND or extensions of the capabilities of KIND RESANN will be required to allow for various pricing policies.

One should expect to find considerable sensitivity to the choices that are made regarding the pricing of water with respect to costs and the elasticity of non-energy users to the price. The testing of such sensitivities will increase both the number of computer runs and the reliability and respectability of the results.

Both energy and non-energy uses of water must be modeled in a manner that permits changeovers to technologies with lower water-use coefficients. Agricultural water users should be permitted to adopt low-water-use irrigation methods or to sell their water rights to energy-related water users. Energy processes should also be modeled as able to switch technologies particularly with respect to the cooling of power plants. We may also wish to handle the case of, say, a slurry pipeline owner who, having acquired the necessary water rights, is unlikely to lower his consumption during the useful life of the pipeline. The present version assumes each user purchases water each year.

The planning and conceptualization of an underlying scenario, of which all scenarios to be run can be variants requiring changes in parameters but not in network structure, is a task logically prior to all others, for which it should be the driving force. This general scenario must incorporate the appropriate regionalization, with aggregation or disaggregation of existng national branches, and specify all options such as alternative technologies that may be active in any particular scenario. When this has been done it will be straightforward to seek answers to questions such as what power companies should do if agribusiness adopts a given strategy or what agribusiness should do given certain government policies on power availability. While at the present time water constitutes a small fraction of the costs of most energy production, it is not too soon to begin asking where and whether these water costs may become the pivot for major decisions.

While the initial impetus for constructing WATER-EPM has come from concerns about the availability of cooling water for power stations, we anticipate further augmentation of the model into problem-specific versions to evaluate climate-energy interactions and imports of policy alternatives with respect to synfuels development.

REFERENCE

1. Nathan Buras, Determining the Feasibility of Incorporating Water Resource Constraints into Energy Models, EPRI Research Project 1304-1, EA-1147, Final Report, August 1979, prepared for Electric Power Research Institute, Palo Alto, CA 94304.

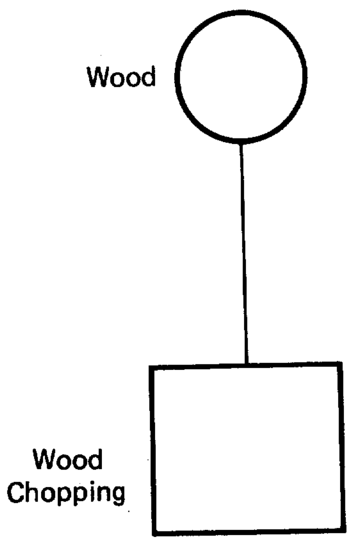


Figure 1

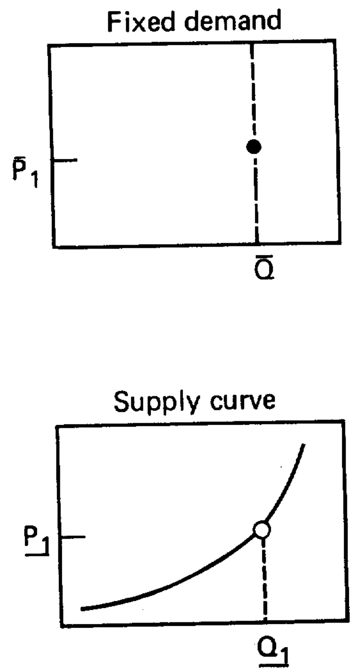


Figure 2

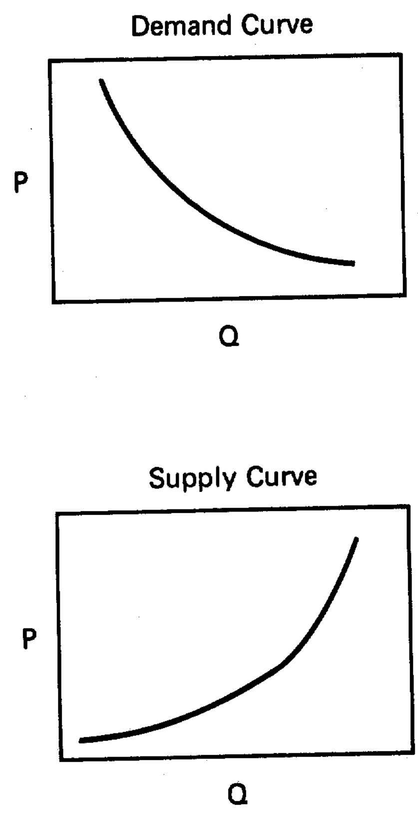


Figure 3

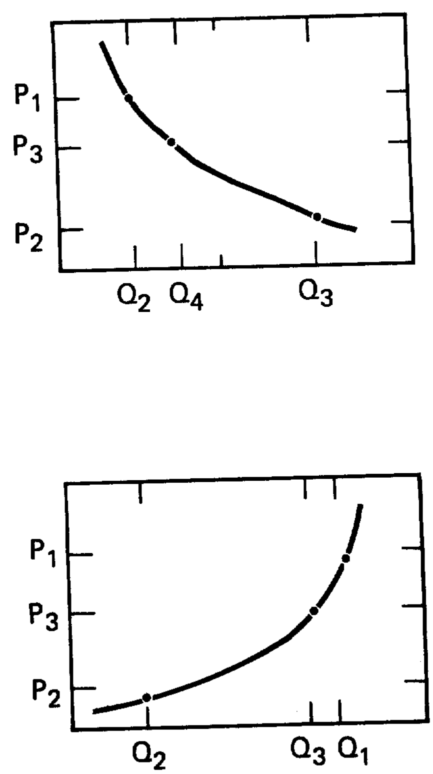


Figure 4

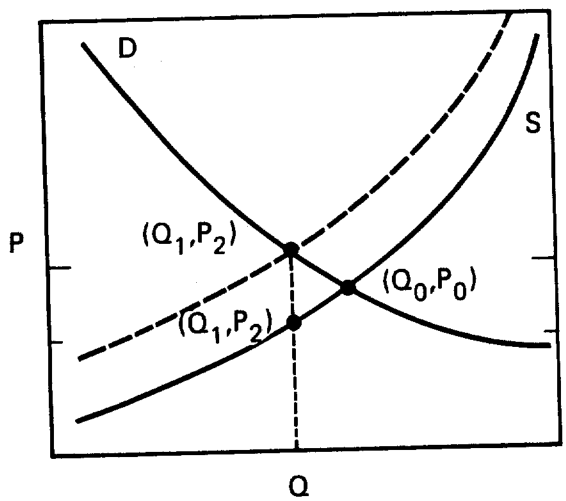


Figure 5

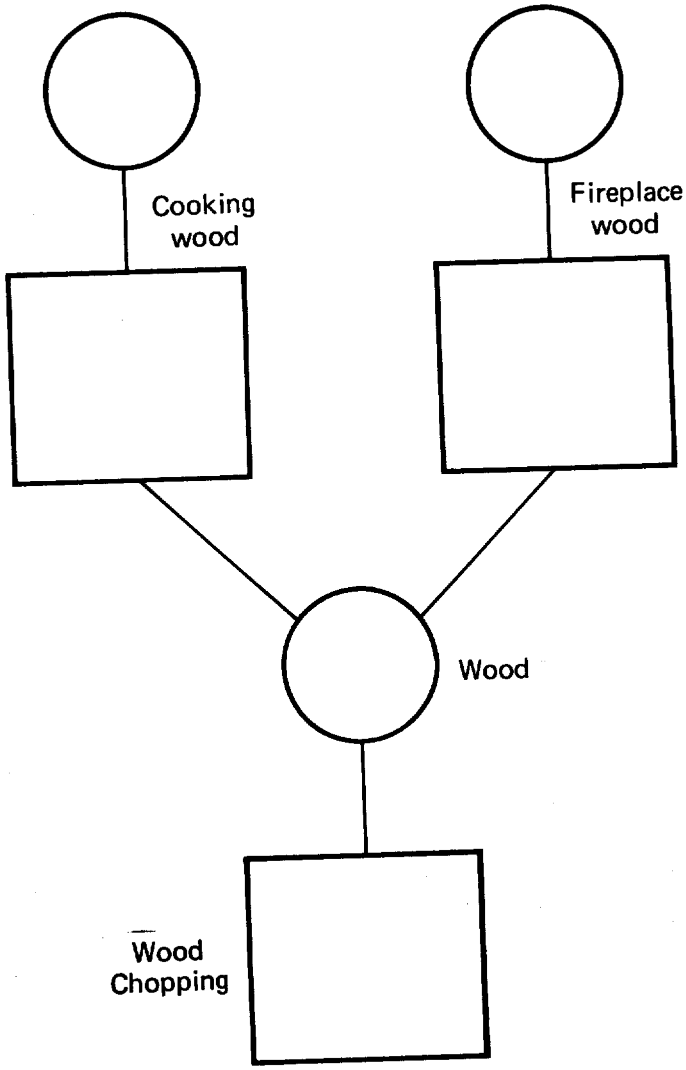


Figure 6

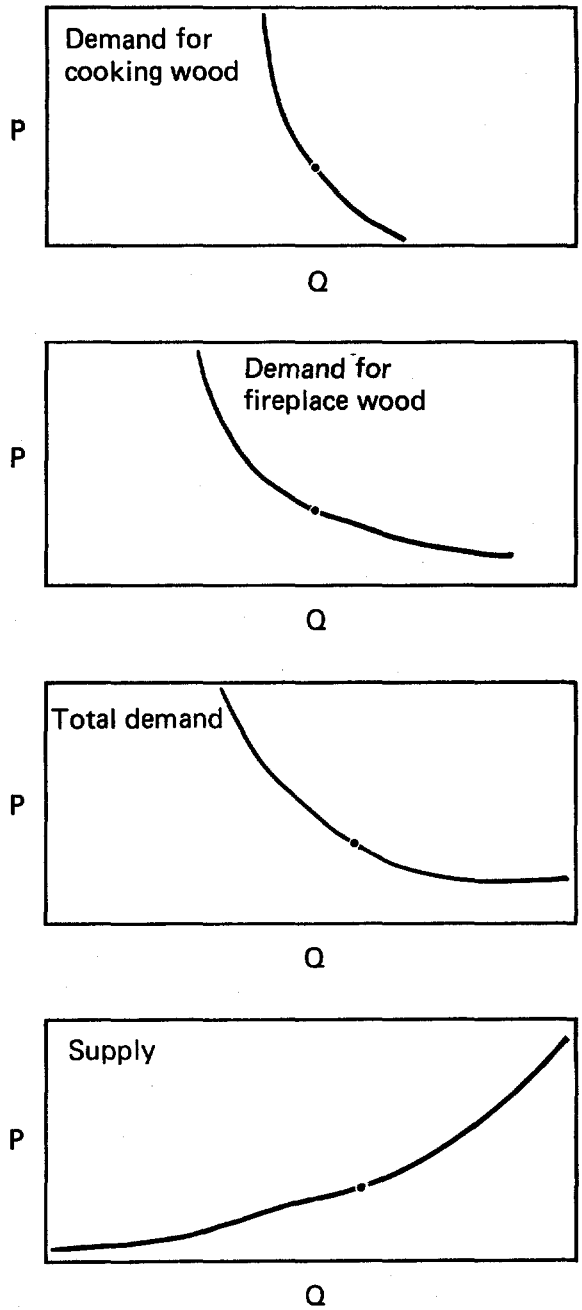

Demand for
cooking wood
P
Q
Demand for
fireplace wood
P
Q
Total demand
P
Q
Supply
P
Q

Figure 7

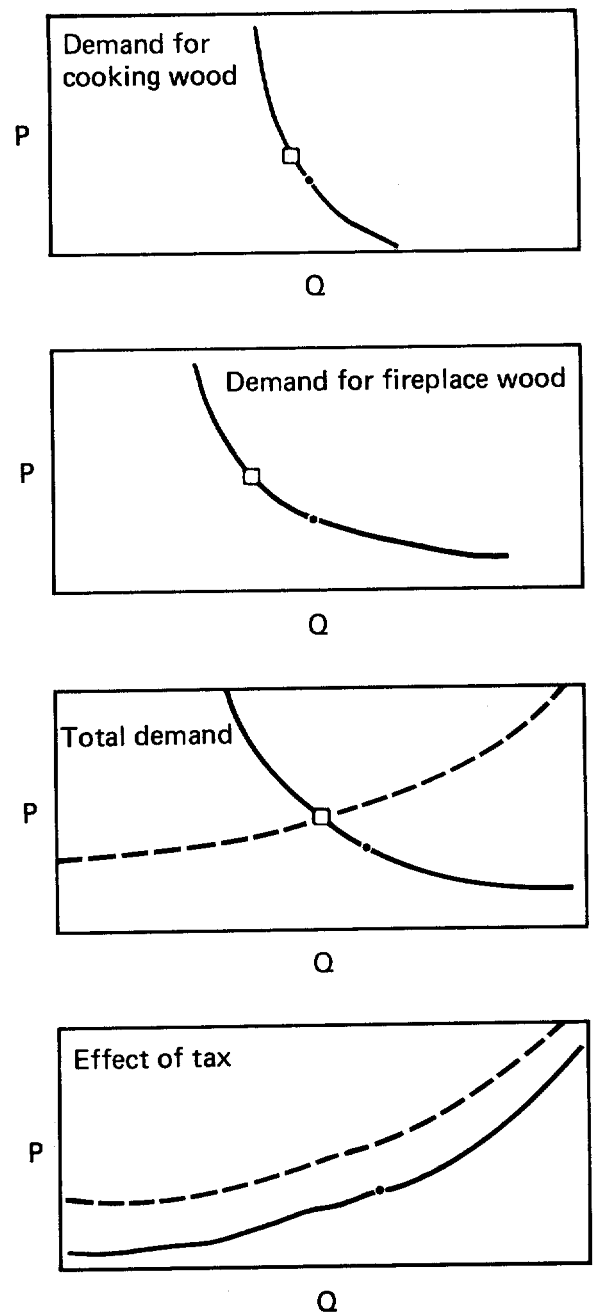
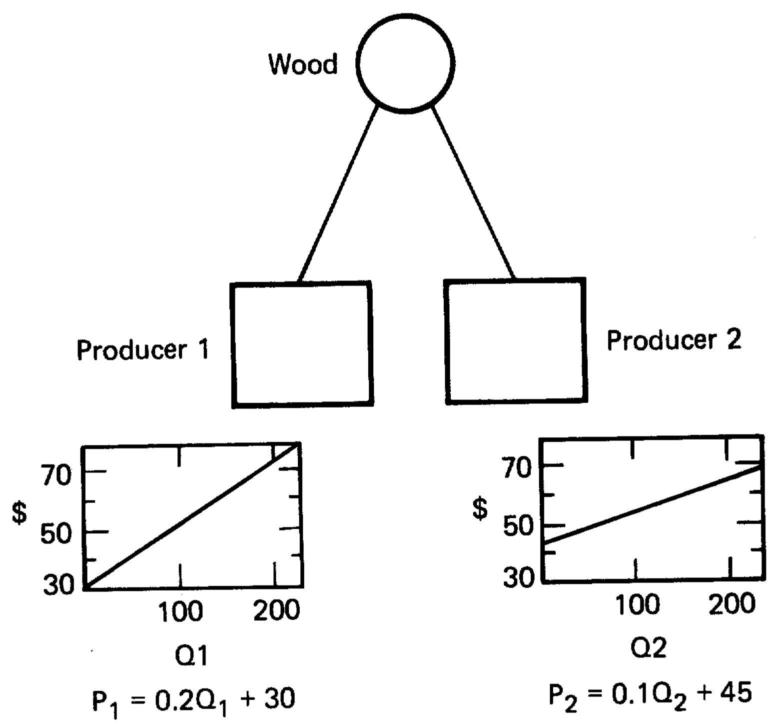
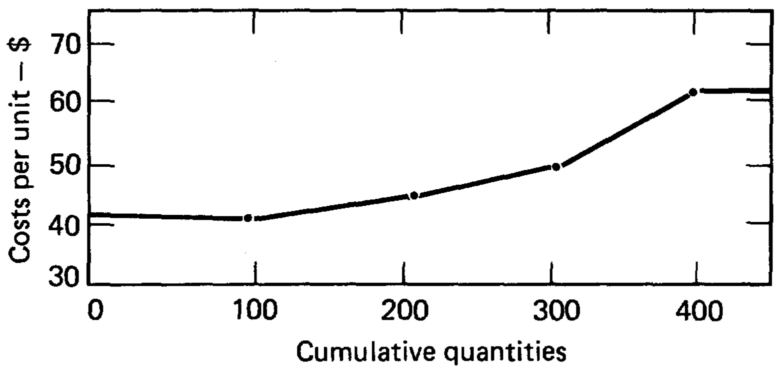

Demand for cooking wood
P
Q
Demand for fireplace wood
P
Q
Total demand
P
Q
Effect of tax
P
Q

Figure 8



Wood
Producer 1
Producer 2
70
$
50
30
100
200
Q1
$P_1 = 0.2Q_1 + 30$
70
$
50
30
100
200
Q2
$P_2 = 0.1Q_2 + 45$

Figure 9



Costs per unit — $
70
60
50
40
30
0
100
200
300
400
Cumulative quantities

Figure 10

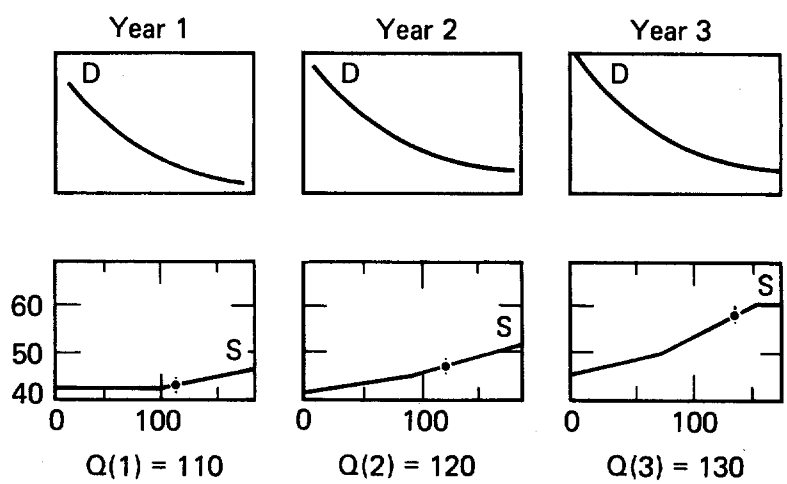

Year 1
Year 2
Year 3
D
D
D
S
S
S
60
50
40
0
100
0
100
0
100
Q(1) = 110
Q(2) = 120
Q(3) = 130

Figure 11

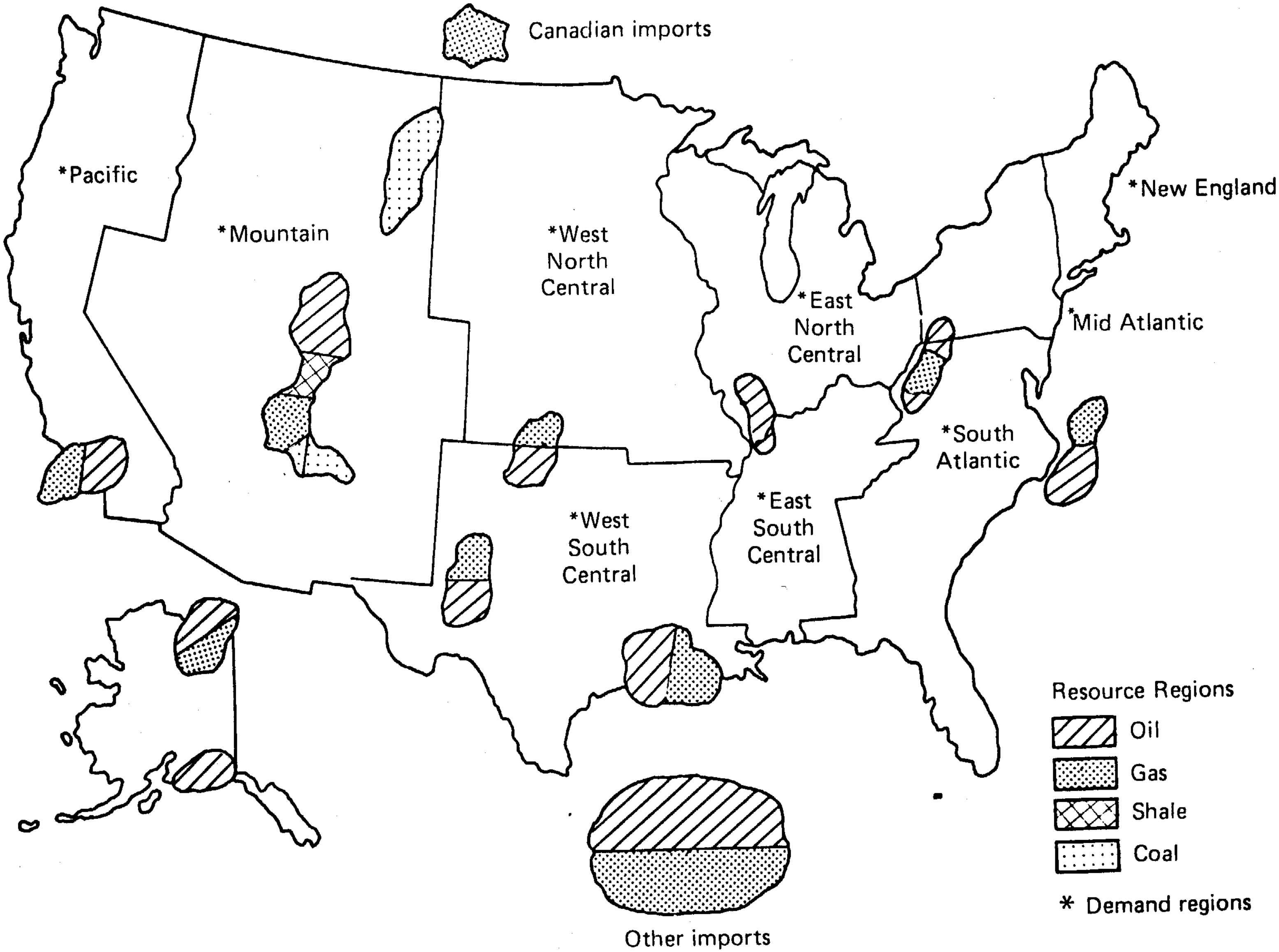

Canadian imports
*Pacific
*Mountain
*West North Central
*East North Central
*New England
*Mid Atlantic
*South Atlantic
*West South Central
*East South Central
Resource Regions
Oil
Gas
Shale
Coal
* Demand regions
Other imports

Figure 12

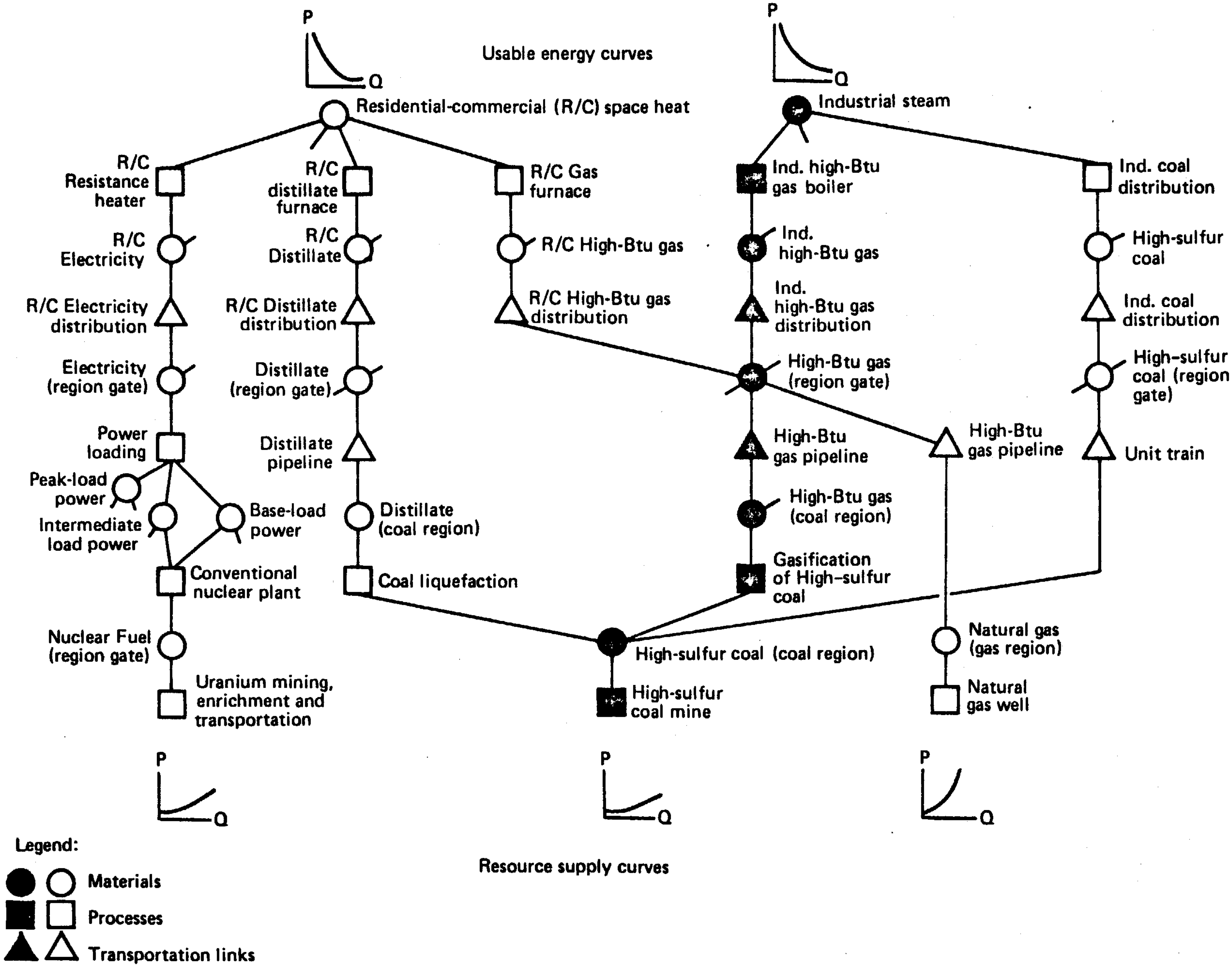
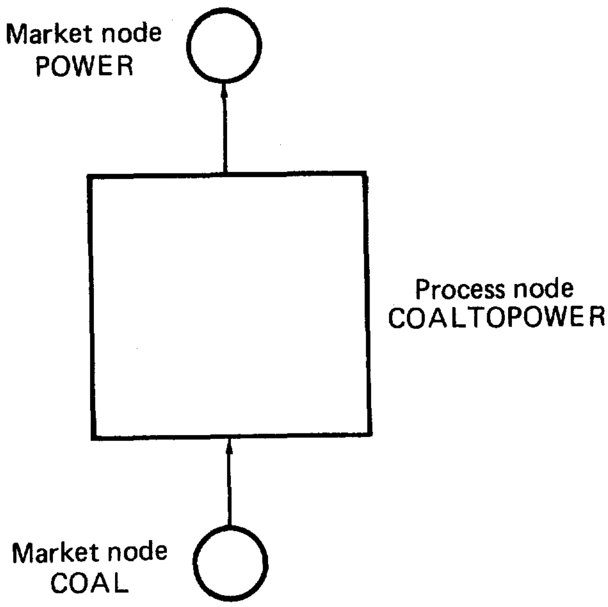

Usable energy curves
P
Q
Residential-commercial (R/C) space heat
Industrial steam
R/C Resistance heater
R/C distillate furnace
R/C Gas furnace
Ind. high-Btu gas boiler
Ind. coal distribution
R/C Electricity
R/C Distillate
R/C High-Btu gas
Ind. high-Btu gas
High-sulfur coal
R/C Electricity distribution
R/C Distillate distribution
R/C High-Btu gas distribution
Ind. high-Btu gas distribution
Ind. coal distribution
Electricity (region gate)
Distillate (region gate)
High-Btu gas (region gate)
High-sulfur coal (region gate)
Power loading
Distillate pipeline
High-Btu gas pipeline
High-Btu gas pipeline
Unit train
Peak-load power
Intermediate load power
Base-load power
Distillate (coal region)
High-Btu gas (coal region)
Conventional nuclear plant
Coal liquefaction
Gasification of High-sulfur coal
Nuclear Fuel (region gate)
High-sulfur coal (coal region)
Natural gas (gas region)
Uranium mining, enrichment and transportation
High-sulfur coal mine
Natural gas well
Resource supply curves
Legend:
Materials
Processes
Transportation links

Figure 13



PROCESS COALTOPOWER (COAL; POWER)

Figure 14

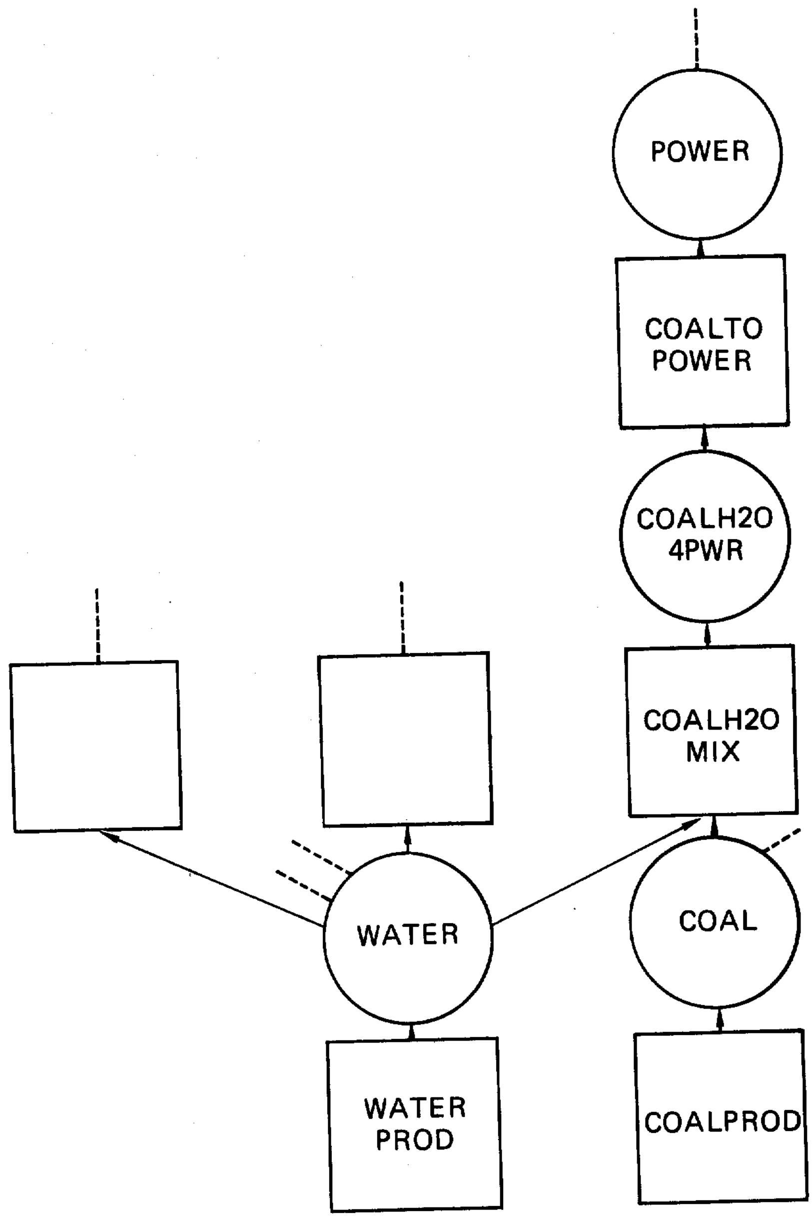
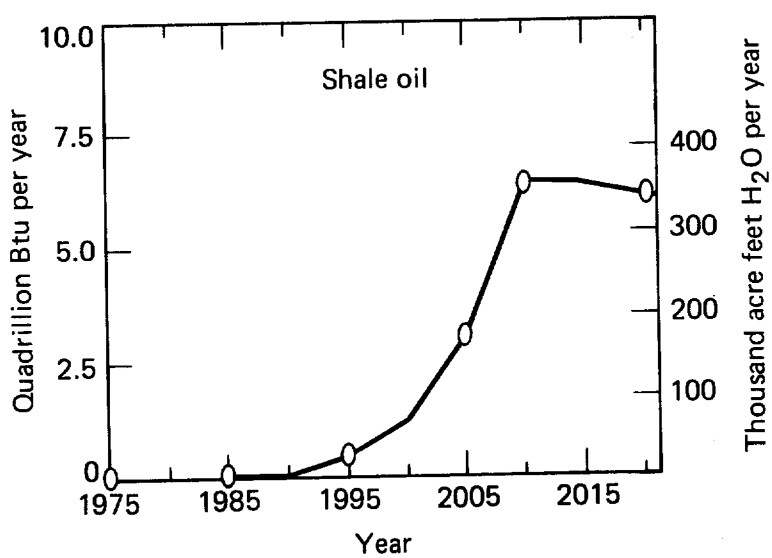

POWER
COALTO POWER
COALH2O 4PWR
COALH2O MIX
WATER
COAL
WATER PROD
COALPROD

Figure 15



Shale oil
Quadrillion Btu per year
10.0
7.5
5.0
2.5
0
1975
1985
1995
2005
2015
Year
400
300
200
100
Thousand acre feet H_2O per year

Figure 16

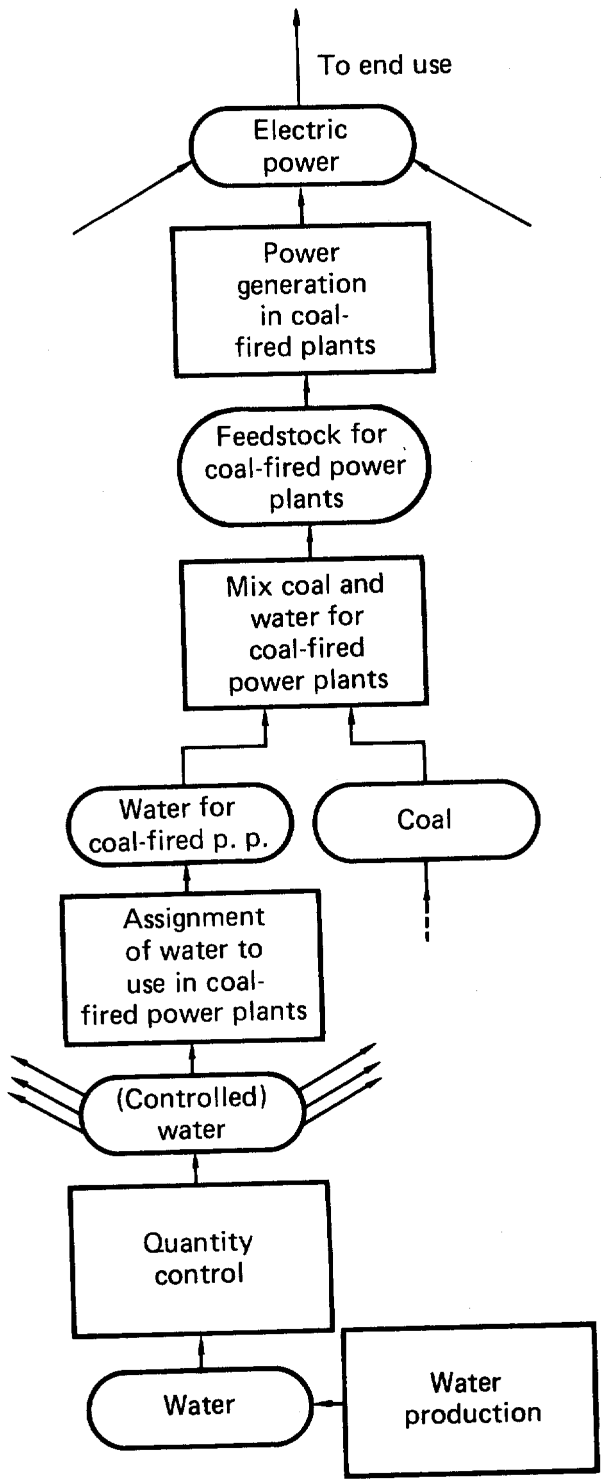

To end use
Electric power
Power generation in coal-fired plants
Feedstock for coal-fired power plants
Mix coal and water for coal-fired power plants
Water for coal-fired p. p.
Coal
Assignment of water to use in coal-fired power plants
(Controlled) water
Quantity control
Water
Water production

Figure 17

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